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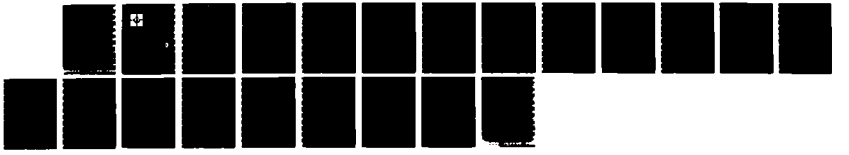

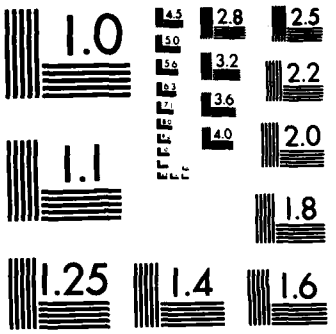


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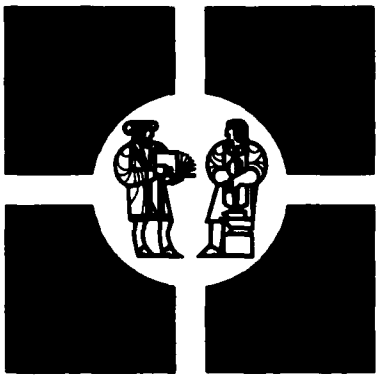

Man-Machine
Systems Laboratory

# Supervisory Control, Mental Models and Decision Aids

**Thomas B. Sheridan**
**Leonid Charny**
**Max B. Mendel**
**James B. Roseborough**

**July 1986**

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This paper poses a framework for considering human supervisory control of semi-automotic systems. It analyzes supervisory control into specific human functions and gives examples of research that have been done and/or are needed with respect to each of these functions. For each such function it is argued that the human supervisory operator necessarily has a corresponding mental model, and potentially can have a computer-based decision aid. The relation of the proposed framework to the canonical modern control paradigm is also discussed, as are the reasonable limitations of our ability to model such a complex human machine interaction which itself exercises a high degree of free choice. Three accompanying papers offer detailed contributions to three of the supervisory functions (and corresponding decision aids) which heretofore have been neglected, namely: (1) formation of objectives by satisficing; (2) acquisition, calibration and combination of measures of process state; and (3) estimation of process state from current measure and past control actions.

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# Supervisory Control, Mental Models and Decision Aids

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*ABSTRACT*

This paper poses a framework for considering human supervisory control of semi-automatic systems. It analyzes supervisory control into specific human functions and gives examples of research that has been done and/or is needed with respect to each of these functions. For each such function it is argued that the human supervisory operator necessarily has a corresponding mental model, and potentially can have a computer-based decision aid. The relation of the proposed framework to the canonical modern control paradigm is also discussed, as are the reasonable limitations of our ability to model such complex human-machine interaction which itself exercises a high degree of free choice. Three accompanying papers offer detailed contributions to three of the supervisory functions (and corresponding decision aids) which heretofore have been neglected, namely: (1) formation of objectives by satisficing; (2) acquisition, calibration and combination of measures of process state; and (3) estimation of process state from current measure and past control actions.

## INTRODUCTION

The term "supervisory control" stems from the analogy between a supervisor of subordinate staff in an organization of people and the human overseer of a modern computer-mediated semi-automatic control system. A supervisor gives human subordinates general instructions which they in turn translate into action. The supervisor of a computer-controlled system may do likewise.

Strictly supervisory control means one or more human operators are setting initial conditions for, intermittently adjusting, and receiving information from a computer that itself closes a control loop through artificial sensors and effectors. Sometimes the term "supervisory control" is used when a computer transforms human operator commands to generate detailed control actions, or makes significant transformations of measured data to produce integrated summary displays. In the latter, less strict definition the computer need not have the capability to commit actions based upon new information from the environment, whereas in the first it necessarily must. The two situations may appear similar to the human supervisor, since the computer mediates both his outputs and his inputs and the supervisor is thus removed from detailed events ot the low level.

Figure 1 diagrams a supervisory control system. The human operator gives commands c to a "human-interactive" computer capable of understanding high level language and providing integrated summary displays of process state information y back to the operator. This computer, typically located in a control room or cockpit, in turn communicates with at least one, probably many (hence the dotted lines), "task-interactive computers". The latter computers thus receive subgoal and conditional branching information from the human-interactive computer; using such information as "reference inputs" they serve to close the low-level control loops between artificial sensors and mechanical actuators, i.e., accomplish the low level automatic control. Since the low level task typically operates at some physical distance from the human operator and his human-friendly display-control computer (located out in a plant, at a remote location on an aircraft or ship, out in space or undersea) the communication channels between computers may be constrained by multiplexing, time delay or limited bandwidth. The task-interactive computer, of course, sends to and receives from the controlled process, and the latter does the same with the environment as it operates (vehicles moving relative to air, sea or earth, robots manipulating objects, process plants modifying products).

The channels of supervisory command and feedback of process state information are shown in Figure 1 to pass through the left side of the human interactive computer. On the right side we represent the decision-aid functions, with displayed output y' being advice relevant to requests or auxiliary information c' which the operator provides. Customarily the latter interaction has not been recognized explicitly as part of a supervisory control system sepatate from the command and state feedback part. New developments in computer-based "expert systems" and other decision-aids for planning, editing, monitoring and failure

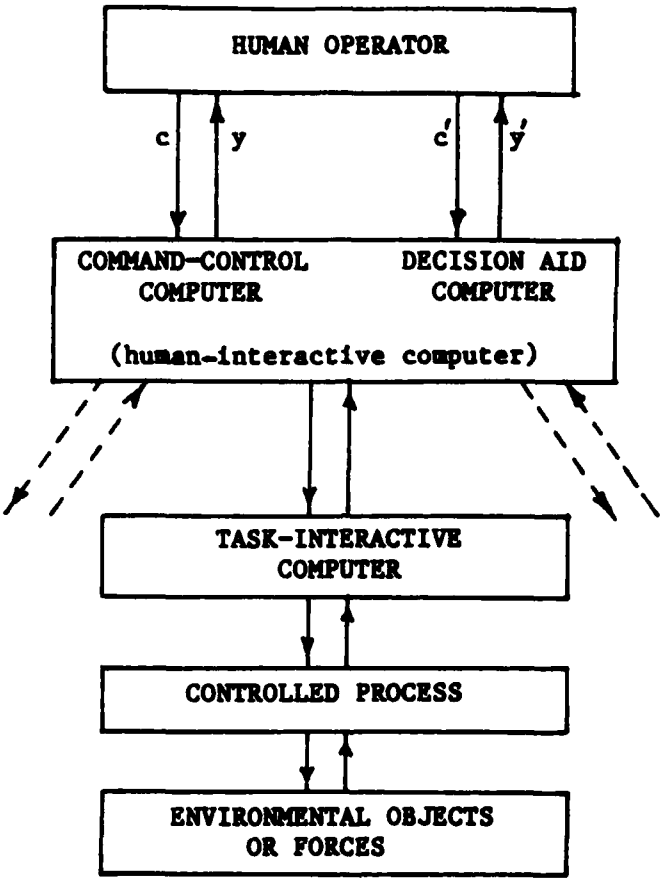


Figure 1. Supervisory Control System

detection have changed that. Further, reflection upon the nervous systems of higher animals reveals a kind of supervisory control wherein commands are sent from the brain to local ganglia, and peripheral motor control loops are then closed locally through receptors in the muscles, tendons or skin. The brain, presumably, does higher level planning based its own stored data and "mental models", an internalized expert system available to provide advice and permit trial response before commitment to actual response.

Initial theorizing about supervisory control began as aircraft and spacecraft became partially automated and it became evident that the human operator was being replaced by the computer for direct control responsibility, and was moving to a new role of monitor and goal-constraint setter (Sheridan, 1960). An added incentive was the US space program which posed the problem of how a human operator on earth could control a manipulator arm or vehicle on the moon through a three second communication round-trip time delay. The only solution which avoided instability was to make the operator a supervisory controller communicating intermittently with a computer on the moon, which in turn closed the control loop there (Ferrell and Sheridan, 1967). It soon became evident that the rapid development of microcomputers was forcing a transition from manual control to supervisory control in a variety of industrial and military applications; the design of display and control interfaces was seen to require a number of new developments (Sheridan and Johannsen, 1976; Sheridan, 1984). The National Research Council (1983, 1984) recently recognized supervisory control as one of the most important areas in which new human factors research is needed; they review a variety of relevant applications and problems.

## FUNCTIONS OF THE HUMAN SUPERVISOR; CORRESPONDING MENTAL MODELS AND DECISION AIDS

Table 1 lists the categories of human supervisor functioning in the order in which they normally would occur in performing a supervisory control task. Figure 2 presents the same sequence of functions in pictorial flow-chart form, where for each function the corresponding mental model is shown as a "thought balloon" of what the supervisor might be asking himself, and the potential computerized decision aid is shown as a rectangular box. The functions are cross-referenced by numbers and letters over each corresponding block in Figure 2. Normally for any given task the first three functions are performed only once and off-line relative to the automatic operation of the system, while the remaining functions are done iteratively, and therefore are shown within two nested loops, as will be explained below.

1a. The first broad category of supervisory functions is PLAN. The first specific supervisor function under PLAN is <u>understand controlled process</u>, which means to gain some understanding of how the given physical thing, equipment or system which is to be operated operates, how it works, what are the relations by which inputs to it become outputs. This is usually the first consideration in training an operator. The idea is to build into the operator a mental model of the controlled process which is appropriate to his role - enough knowledge

| Supervisory Step | Associated Mental Model | Associated Computer Aid |
|---|---|---|
| 1. PLAN | | |
| a) understand controlled process | physical variables; transfer relations | physical process training aid |
| b) satisfice objectives | aspirations; preferences and indifferences | satisficing aid |
| c) set general strategy | general operating procedures and guidelines | procedures training aid; optimization aid |
| d) decide and test control actions | decision options; state-procedure-action implications; expected results of control actions | procedures library; action decision aid (in-situ simulation) |
| 2. TEACH | | |
| decide, test and communicate commands | command language (symbols, syntax, semantics) | aid for editing commands |
| 3. MONITOR AUTO | | |
| a) acquire, calibrate and combine measures of process state | state information sources and their relevance | aid for calibration and combination of measures |
| b) estimate process state from current measure and past control actions | expected results of past actions | estimation aid |
| c) evaluate process state; detect and diagnose failure or halt | likely modes and causes of failure or halt | detection and diagnosis aid for failure or halt |
| 4. INTERVENE | | |
| a) if failure: execute planned abort | options and criteria for abort | abort execution aid |
| b) if normal end of task: complete | options and criteria for task completion | normal completion execution aid |
| 5. LEARN | | |
| a) record immediate events | immediate memory of salient events | immediate record and memory jogger |
| b) analyze cumulative experience | cumulative memory of salient events | cumulative record and analysis |

Table 1. Functions of the Human Supervisor

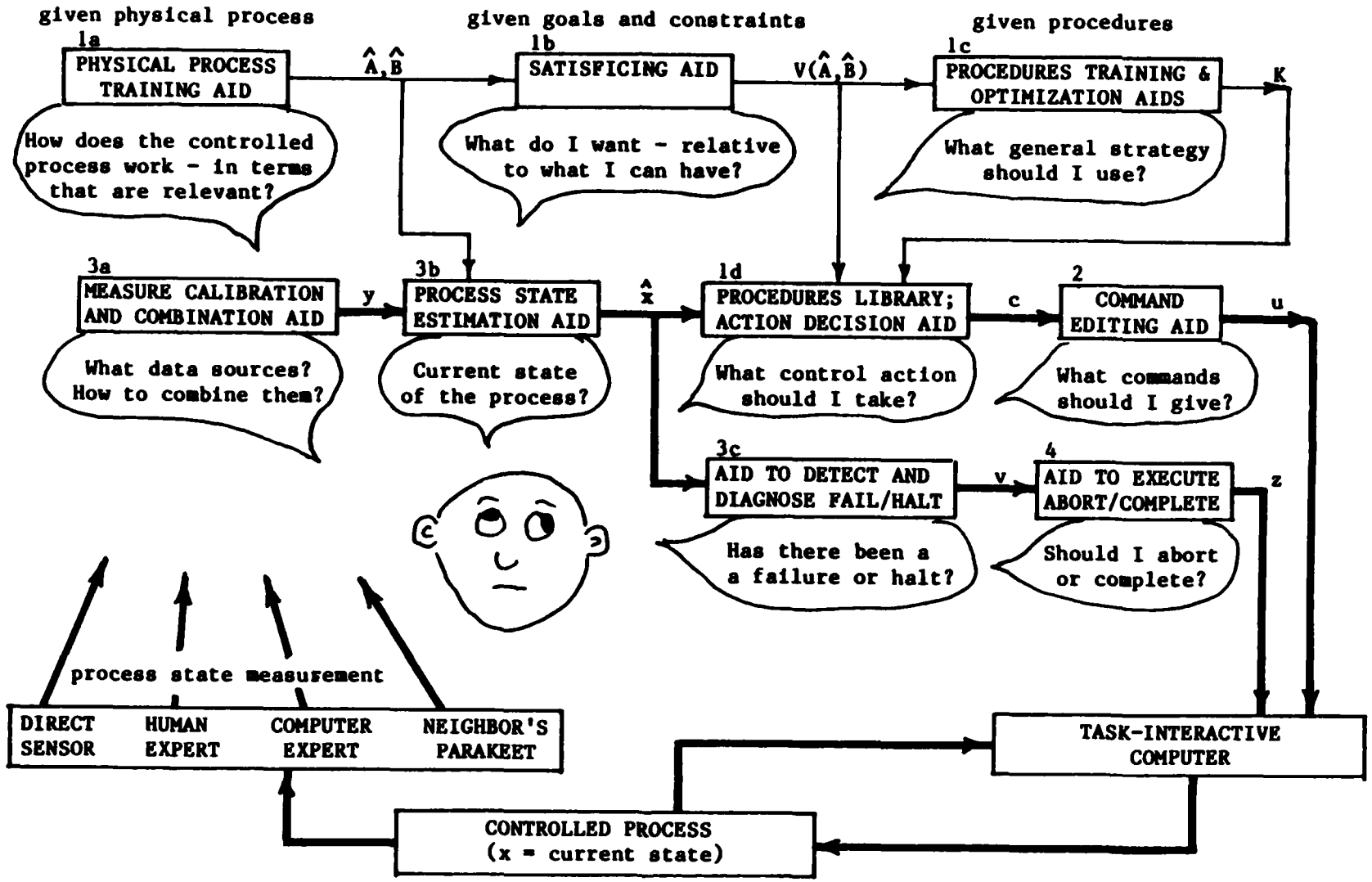


Figure 2. Computer-Based Decision Aids (boxes) and Mental Models (thought balloons) Corresponding to Each of the Supervisor's Functions

of the appropriate variables and their input-output transfer relations to be able to control and predict what the process will do, but not details that are irrelevant to operation. The current research on mental models (de Kleer, 1979; Gentner and Stevens, 1983) has tended to concentrate on this function. A new generation of computer-based training aids has been developed recently which includes computer representation in terms of production rules, semantic nets, frames or other AI manifestations which has encouraged this emphasis (Holland et al, 1984; Harmon and King, 1985).

1b. The second specific function under PLAN is satisfice objectives. To control engineers this corresponds to obtaining an objective function, a closed-form analytical expression of "goodness" which is a scalar function of all relevant variables or "performance attributes" or "objectives". To a mathematical decision theorist it may correspond to a multiattribute utility function, which specifies the global and unchanging relative goodness or badness of any point in the hyperspace of all relevant attributes (Keeney and Raiffa, 1976). However the behavioral decision scientist knows that neither of the above models of human preference works very well in practice, that people find it extremely difficult to consider levels of attributes that they have never experienced, and hence they cannot provide reliable data from which to generate global objective or utility functions. What appears much closer to the way people actually behave is what has been termed "satisficing" (March and Simon, 1958; Weirzbicki, 1982), wherein a tentative aspiration point in attribute space is set and the decision-maker considers whether he can achieve this. But upon discovering that constraints will not permit this, or that he can achieve something more that what he aspired to, he will set a new aspiration level and consider whether he can achieve that, eventually deciding on the basis of time and energy spent in thinking about it that he is satisfied with some one set of objectives, some single point or small indifference region in attribute space.

The computer may provide aid by determining for any aspiration point whether it can be achieved, or whether or in what direction he can do better, all the while reminding him what set of options are pareto optimal, i.e., not dominated by a point in attribute space which is not worse in any attribute and is better in one or more. Charny and Sheridan (1986), in one of the three papers accompanying this one, describe the development of an interactive computer-graphic aid to help a supervisor "satisfice". The tool allows the user to set range constraints on the attributes, set weights, or set partial solutions. The aid then displays the implications in terms of what is feasible and what is not, what are "optimal" solutions, how the selected "optimum" relates to other decision possibilities in multiattribute space, and perhaps most interesting, how much the weights or constraints must change in order for a different "optimum" to emerge - in other words a running sensitivity analysis. Using such a tool the supervisor may be expected to be influenced at least to some degree by goals given "from above" by employer, professional training, laws of the government, early upbringing, or social/cultural mores. Nevertheless, as systems become more automated in their actual control, the free-will imposition or "tuning" of task goals (objective function set by a satisficing process)

is the one function that would seem impossible to automate.

1c. The third specific function under PLAN is set general strategy. The supervisory operator is usually given some procedures or operating guidelines which he is to follow generally (or to deviate from as required for the particular task at hand). This is the third function which is usually performed off-line, before the automatic system starts up. It is the second activity usually addressed formally in training programs (objective function setting is typically not addressed formally, though it might well be). The mental model here is that of the general operating procedures and guidelines which must be committed to memory (where detailed procedures can be accessed and read as needed). The corresponding computer aid here is one for procedures training. To help the supervisor relate the strategy planning to the satisficed objectives there might also be an aid for optimization in a broad sense, particularly when the general procedures are not already formulated and where certain goals are given and are not to be modified. Any of a number of common operations research techniques might be applied here, depending upon the class of tasks.

1d. The fourth specific function under PLAN is decide and test control actions. To decide control actions, of course, is by definition the essential function of any controller and the supervisory controller is no exception. On the first pass of stepping through the supervisory functions this function would consist of the actions necessary to start up the automatic system, but on successive passes the specific control decisions must necessarily be based on feedback of state. The supervisor's job is then to decide what procedures are appropriate for the estimated state and what specific actions are implied, in consideration of process dynamics and satisficed objectives as mentally modelled in steps 1a, 1b and 1c. One form of decision aid for this function, already employed in some modern nuclear power and process control plants, is a computerized system which, upon it's own estimation of process state, displays to the operator the preplanned procedures which most fit that plant condition. These are not implemented automatically, though in some cases they could be, for it is deemed important to give the human supervisor some room for interpretation in light of his knowledge about process or objectives that are not shared by the computer. Kok and Van Wijk (1978) modeled this decision function in a simple supervisory control context. Baron et al (1980) developed a decision model of aircrew supervisory procedures implementation which they term PROCRU and which is built on their earlier optimal control model.

Because supervisory control is discontinuous and because each packet of commands constitutes a commitment for some period of time and some sequence of process responses, it is appropriate that the supervisor test out his commands on some form of off-line simulator before committing them to be executed in the real system. Part of the mental activity for this function is the exercise of an internal model to yield expected results of hypothetical control actions, i.e., "what would happen if - -?" (where "happen" means both physical response of the controlled process and resulting goodness of performance relative to objectives). The internal model prediction may then be compared to the

results from the computer simulator test. Early models of supervisory control embodied this idea (Sheridan, 1976). Yoerger (1982) implemented such a test capability in his supervisory manipulation interface, whereby the operator could see a graphic display of just where a manipulator arm would move relative to a workpiece on the basis of given commands. The idea of testing out commands before committing them to action has had many antecedants, both in computer control and in behavioral models. For example Rasmussen (1976) included a dynamic world model in an early version of his multilevel model of behavior.

2. The next supervisory function is TEACH, which means to decide, test and communicate commands necessary to give the computer in order that it be able to implement the intended actions. It is essential at this point to make a clear distinction between commands and control actions, since in normal control engineering practice and indeed normal activities of living they may be taken to be the same. Commands are the operator's movements of analogic control interface devices such as joysticks, master manipulator arms, or computer screen cursor controls, and his stroking of symbolic alphanumeric and special function keys, while control actions are the responses the human-interactive computer makes to these commands to signal the task-interactive computer, activate motors or other actuators, and thereby force the controlled process to modify its state. The mental model in this case is the command language (the set of admissible symbols or words or movements, the syntax or rules for their combination, and the semantics or meanings of both individual symbols and combinations). The computer aid in this case is an editing aid, an interactive means to help the user say to the computer what it needs to hear in order to do what the operator wants done. This is not unlike an editing aid for word processing or for programming in general, where the computer informs the user what commands are not interpretable, and might come back and suggest what might be meant, etc.

There have been many developments of supervisory command languages. In modern aircraft there are several levels of commands for setting the autopilot (e.g., going to and holding a new altitude, flying to a set of latitude-longitude coordinates on the other side of the earth, making an automatic landing (Yoerger, 1979). In industrial robotics various protocols have been developed for using "teach" pendants to program simple instruct-move-playback routines. More sophisticated symbolic command structures have enabled the teaching of arbitrarily defined terms, conditional branching, etc. (Nof, 1985). Flexible combined analogic-symbolic command languages such as SUPERMAN (Brooks, 1979; Yoerger 1982) have been developed to allow very fast and natural instruction of telerobots. Supervisory languages currently under development promise the user the capability to use fuzzy (imprecisely defined) commands (Yared, 1986).

3a. The next category of supervisor functions is MONITOR AUTO, meaning the human operator monitors the automatic execution of the progammed actions. This includes three separate functions, the first of which is acquire, calibrate and combine measures of process state. This requires that the supervisor have a mental model of potential sources of relevant information, their likelihood of knowing about particular variables of

interest, and their likely biases in measuring and reporting. The point is that there can be many sources which have something to tell about any one variable: real-time sensors, computerized data bases and "expert systems", human experts, and incidental sources which are likely to be unreliable but may provide some useful evidence. Some sources advertise themselves as being very precise but may not be, others may be much more precise than first expected. Some may be consistently biased, so that if only the bias could be removed they would provide very accurate measurements. If a computerized aid could help sort out which sources were in fact precise and which were not, could remove biases and could combine data sources to provide corroboration and a better statistical sample, that could be a real boon to the human supervisor. Mendel and Sheridan (1986) have done just that, and their description of this work is described fully in a second accompanying paper.

3b. The next function to follow is estimate process state from current measure and past control actions. Estimation theory provides a normative way to do this, which is commonly used in modern control practice. This requires a good model of the physical process, which is not ordinarily available in complex systems controlled by a human supervisor. Presumably the human supervisor has some internal (mental) model of how past control actions should be affecting present process response, and tries to combine this with his best (but likely to be inaccurate) direct measurement data on current process state in order to form a best overall estimate of current state. But this is not easy for a person, especially if the system is complex. However for a computer, given a good model of the controlled process and a single best measurement of its state (which still is likely to be imperfect), it is relatively straightforward to calculate the best estimate of current state. The problem then comes in displaying this to a human operator in a way which is meaningful and useful.

Roseborough and Sheridan (1986), in the third companion paper, describe experiments wherein human controllers of partly deterministic, partly stochastic processes (which is characteristic of real supervisory control systems) are provided with such normative decision aids. Results show that operators cannot accommodate cognitively all of the state information which a full formal estimate makes available, and suggest how operators take various shortcuts to simplify their cognitive tasks in making use of the advice given them.

It might be noted that each of many separate measurements of process state could involve internal models (using Kalman estimation or other model-based techniques). These multiple estimates might subsequently be combined by Bayesian or other methods. Thus it is conceivable that function 3b precede 3a.

3c. The third supervisory function under MONITOR AUTO is evaluate process state; detect and diagnose failure or halt. This means that the operator maps state information relative to the satisficed objectives (which may not be straightforward if the estimated state is outside the region of attribute space in which satisficing was done). He must detect and diagnose whether the process has "failed" (strayed sufficiently far from expected objectives) or whether it has halted

(stopped before the commanded actions were all executed without getting into trouble) and to some extent must diagnose where and how. The mental model accordingly incorporates, in addition to the state estimate available from 3b, the likely modes and causes of failure or halt. The computer aid in this case is an aid to the operator for detecting and diagnosing the location and cause of failure or halt. Recently there have been a number of computer aids developed for this purpose, some of which are based on statistical estimation theory (Curry and Gai, 1976), some of which are based on discrepancies between measured variables and component models (Tsach et al, 1983), and some of which are based upon production rules and other AI techniques (Scarl et al, 1985).

4a. The next supervisory function is INTERVENE, which is conditional upon detection of a failure or halt condition. If failure: execute planned abort means that when the state has deviated sufficiently far from what is desirable - or supervisor judgment and/or the computer-based failure detection suggests that it will - the supervisor promptly executes an already programmed appropriate abort command. His mental model is of a relatively small number of preplanned abort commands and their criteria for use. A computer decision aid in this case can advise him of which to use and how to use it.

4b. If there is no failure and the process has halted when it was expected to, the supervisor must bring the task to completion (execute an appropriate completion command). That is, if normal end of task: complete. His mental model is of a relatively small number of preplanned commands to finish off the task, a kind if inverse to the startup, and he should have some knowledge of their criteria for use. As in 4a the computer decision aid can advise which to use and how to use it. If there is no failure and the halt condition does not call for normal completion the operator is not likely to have a simple preplanned open loop command at the ready, and must cycle back to 1d for a more considered execution of the next step in supervisory command and computer controlled execution. But before he does there is one important function to perform.

5a. Because of the complexity of systems which lend themselves to supervisory control the recording of what was considered, what was commanded, and what happened cannot be left to informal chance. It is an important function of the human supervisor not only that he update his own experiential mental models but that he also ensure that some computer-based records are kept for later use. When there is neither failure nor completion and the supervisor is ready to cycle back to 1d the LEARN function only means record immediate events so that there be some immediate human memory of significant events and an update of computer records. In this case it is helpful if the computer aid also provide some "memory jogging" display such as a chart of recent state trajectories, or a listing alarms or other key events (as is commonly done in nuclear power plants).

5b. When the task is terminated either by abortion in response to failure or by normal completion it is then important to exercise the LEARN function in a more extensive manner. In this case analyze cumulative experience means that the supervisor should recall and

contemplate the whole task experience, however many command cycles there were, so as to improve his readiness when called upon for the next task. The computer aid in this case should provide some cumulative record and analysis in a form that can be accessed and used later during the PLAN phase.

Thus it is claimed that a sequence of three initial functions, an iterative loop of eight additional functions, and one final function characterize what a human supervisor does (or should do) in a variety of complex supervisory control systems. The outer loop shown in Table 1 merely suggests what happens when undertaking a new task.

## SUPERVISORY CONTROL AND THE CONVENTIONAL CONTROL PARADIGM

Figure 2 showed a diagram of a supervisory control system representing the sequence of supervisory functions as they relate to the key system variables, the task-interactive computer and the controlled process. Figure 3 takes this same set of variables and interrelates them in the format of the canonical modern control paradigm - modified as necessary to include all the functions and additional variables that have been discussed above. As with Figure 2, Figure 3 cross references the functions of Table 1 with numbers and letters at the upper left of each block.

At the top of Figure 3 the three "off-line" planning functions 1a, 1b, and 1c are shown in sequence as in Table 1 and Figure 2. At successive stages the process mental models of natural process response A and forced process response B, the mapping of state attributes to objectives V and the general operating strategy K are generated. When K is used on-line and in-the-supervisory-loop (function 1d) it takes as inputs not only the state estimate x fed back from 3b but also the evaluation fed back from 3c.

The mental model parameters $\hat{A}$ and $\hat{B}$ which are essential for 3b are intended by the operator to correspond to the actual physical process parameters A and B. The parameter C, in turn essential to feed 3b, represents the combination of physical sensors attached to the process and the human and computer "expert" resources actively accessed, calibrated and combined by the human supervisor and/or a computer aid. Hence C represents the whole of the 3a computer process, much more than just a passive measurement matrix. $\hat{C}$ represents the 3a mental process and the discrepancy between y and $\hat{y}$ which drives G is the degree to which expected results of past actions u (3b) are insufficient to completely predict y so that there must be a correction through G.

E represents the communication or TEACH interface (function 2), the transformation of analogic and symbolic commands into control actions by the computer(s). F represents the INTERVENE interface (function 4), the detection and diagnosis of a failure or halt condition and the possibly resulting abort or completion commands which by-pass the usual communications interface E. At the lower left the models $\hat{E}$ and $\hat{B}$ are necessarily in tandem.

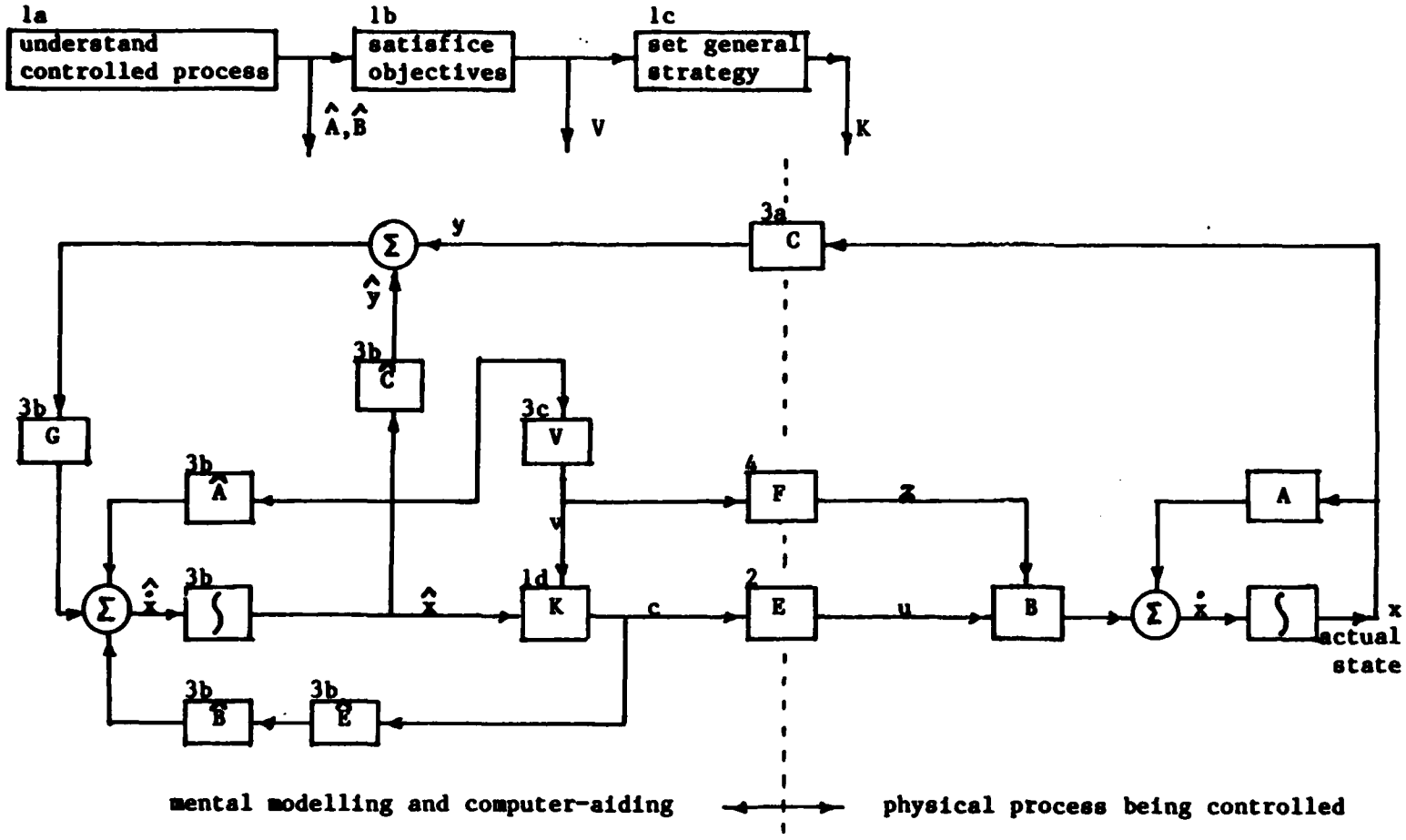


Figure 3. Supervisory Control in the Form of the Canonical Control Paradigm
A = natural physical response of controlled process; $\hat{A}$ = mental/computer model
B = forced physical response of controlled process; $\hat{B}$ = mental/computer model
C = physical/human measurement of state; $\hat{C}$ = mental/computer model
E = normal command interface; F = abnormal or intervention command interface
G = discrepancy gain for state estimation; K = general control decision strategy
V = satisficed objectives, including failure and halt criteria

Together the parameters $\hat{A}$, $\hat{B}$, $\hat{C}$, G and K constitute the fully internalized mental model of the supervisory controller operating in the iterative or "in-the-supervisory-loop" mode much as they do in the Baron-Kleinman-Levison optimal control model of the human controller. In the supervisory control case, however we explicitly add the parameter V as an internalized mental model, and call for the recognition of C, E and F as interface parameters which make a critical difference in how the whole system functions. A and B of course are the same parameters as in the conventional control paradigm. The 1a, 1b and 1c blocks are necessary add-ons to achieve the required meta-control or parameter generation.

As yet no analytic functions have been put in all of the blocks, even those in the closed-loop portion of Figure 3, such that analysis, simulation and modeling follow easily and naturally therefrom. That is a further step.

## FACTORS WHICH LIMIT OUR ABILITY TO MODEL SUPERVISORY CONTROL SYSTEMS

There are two factors which limit our ability to model supervisory control systems, apart from the fact that they tend to be complex.

The first factor is the same as that which makes any cognition difficult to model. As compared to direct manual control, the essence of supervisory control seems to involve cognition, or mental activity, particularly involving objectives and command/contol decisions made at least partly by the free will of the supervisor. The problem is that such mental events, especially when the task is relatively unconstrained, are <u>not directly observable</u>; they must be inferred. This is the basis for the ancient mind-body dilemma, as well as the basis for the more recent rejection by behavioral scientists of mental events as legitimate scientic concepts. Such "behaviorism", of course, is out of fashion now; computer science begat behavioral science and by indirect inference made computer programs admissible representations of what people think. However the limits on direct measurement of mental events do not seem to want to go away.

The second factor is more specialized to supervisory control. It is a result of mental models internal to the human operator and computer decision aids external to him being used freely together. If the operator chooses to follow the aid's advice what can be said about his exercising of his own mental model? If he claims to "know" certain facts or have a "plan" which happens to correspond to the knowledge or plan in the computer, can the normative decision aid be considered a convenient yardstick against which to measure inferred mental activity? Where there is free interaction between the two it is difficult to determine what is mental and what is computer, i.e., mental and computer models are more easily treated as a combined entity which produces operator decisions.

In spite of these difficulties we must continue efforts to model and predict human behavior in this more and more prevalent form of control system.

## CONCLUSION

Twelve sequential functions of the human supervisor of a semi-automatic control system are characterized in detail, together with a review of relevant research. For each function a mental model is assumed and a computer decision aid is suggested. The elements of this functional model of supervisory control are related to the elements of the canonical model of modern automatic control. Two factors which ultimately limit our ability to model human behavior in such situations are presented.

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